The Role of Fuel Cells in the Supply of Silent Power for Operations in Littoral Waters

Dr J B Lakeman
Physical Sciences Department
Room 18, Building 352
Dstl Porton Down
Salisbury, Wiltshire SP4 0QR
UK

Dr D J Browning
QinetiQ Centre for Marine Technology
Haslar, Gosport
Hampshire PO12 2AG
UK

ABSTRACT

Stealth is an important factor in littoral operations. Stealthy power sources for underwater vehicles include air-independent propulsion technologies, such as fuel cells, perhaps hybridized with an energy store such as an advanced battery. The hybrid combination provides the most covert solution, with good underwater endurance. Of the fuel cell technologies examined, the proton exchange membrane fuel cell (PEMFC) currently offers the best performance, and we review relevant fuel and oxidant options. For the very long transit patrols of large submarines, nuclear power must be a component of the solution but perhaps as part of an integrated hybrid power source system rather than as the sole main power source.

INTRODUCTION

There is an ever increasing requirement for stealthy underwater platforms such as swimmer delivery vehicles, unmanned underwater vehicles, submarines, weapons and mobile countermeasures. Hence, there is a desire to reduce noise levels and indeed detectable emissions of all types.

In parallel, there is a move towards all-electric platform concepts and weaponry for naval platforms that will result in potentially stealthier platforms and pulse-power, lower signature weapons. Storing and generating electric power is therefore of major interest, both for propulsion over long distances and also for pulse-power weapons.

In this paper, we focus on fuel cells as a means of meeting stealth and performance targets for different underwater platforms.

POWER SOURCES FOR PRESENT AND FUTURE UNDERWATER PLATFORMS

Power sources can be classed as either power generation or energy storage devices. The nuclear submarine (SSN), for example, has three power sources:

Table 1: The Three Power Sources on the Current Nuclear Submarine

Role	Current power source
Primary power source	Nuclear steam raising plant (NSRP)
Auxiliary power source	Diesel generator
Emergency energy storage	Lead acid battery

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The NSRP, harnessed through steam-driven, turbo-generators (TGs), provides all the power for normal submarine operations and can be made acceptably stealthy. The diesel generators (DGs) supply enough power for limited air-breathing propulsion, but are inherently noisy. They maintain submarine and nuclear safety systems when the NSRP is unavailable and the vessel is surfaced or snorting, supplement shore-service power during reactor start-up, and supply boat power during 'cold moves', etc. The lead-acid battery stores sufficient covert power to sustain submarine systems for a short time following temporary loss of the NSRP. Should NSRP power not be restored, it will be necessary to use the DGs, which means operating the submarine at periscope depth or surfaced, thereby increasing its vulnerability.

A conventional, non-nuclear submarine (SSK) has only two power sources: a battery for submerged, covert operations and, a diesel generator for surface transit (or snorting), and battery charging. The battery on the SSK tends to be bigger than that on the SSN, typically storing 2 to 4 times the energy and so providing reasonable submerged endurance, albeit nowhere near that of SSNs.

A submarine is vulnerable to detection when surfaced or snorting, so there is a demand for increased submerged endurance, particularly in the littoral. For SSKs in particular, the development of a stealthy, high performance, air-independent propulsion system is a key requirement. For SSNs, substituting the air-breathing, emergency DGs, by an air-independent propulsion (AIP) power source, would extend emergency underwater operation and reduce detectability.

Smaller underwater platforms currently use batteries – for example, low cost lead-acid batteries for vehicles having short missions and alkaline primaries for longer ones. For mission critical, military applications, more exotic, high performance systems are used such as zinc-silver oxide primaries or lithium-ion secondary batteries. However, fuel cells have the potential to significantly increase the underwater endurance of such platforms.

Air-Independent Propulsion Power

To avoid detection, a submarine should remain submerged, ideally using stealthy power sources. For an SSK, AIP improves submerged endurance, removes any requirement for intake and exhaust connections through the surface, and immediately reduces the chances of detection by visual, radar or even thermal methods.

In its simplest form, the AIP power source is a battery. The ideal AIP power source for a submarine will be quiet, have a low thermal signature, will not need to discharge any detectable contaminants, and will of course be capable of operating without atmospheric air. In principle, there is no reason why hybrid, air-independent power should not be used for all sizes of platform.

The AIP system is likely to be a hybrid combination of power generators and energy storage devices, ideally by replacing the diesel generators in submarines with fuel cells. The energy storage device will supply peak and pulse power, power for start-up of the power generator and continuous power for a minimum specified duration. The power generator will supply base-load power, and will recharge the energy storage device. A hybrid AIP configuration might be feasible for smaller, unmanned underwater platforms, depending on the required submerged endurance.

FUEL CELL SYSTEMS

The fuel cell is not the only option for AIP-others include the Stirling engine, the closed-cycle diesel generator, and the French MESMA system. These alternatives are mechanical devices relying on moving parts, with a lower potential fuel and oxidant efficiency; this is illustrated by the oxygen consumption rates in Figure 1. The fuel cell, which is an electrochemical energy converter, offers the greatest potential for stealthy, submerged operation, both for manned and unmanned platforms, and the rest of the paper will focus on this power generation technology.

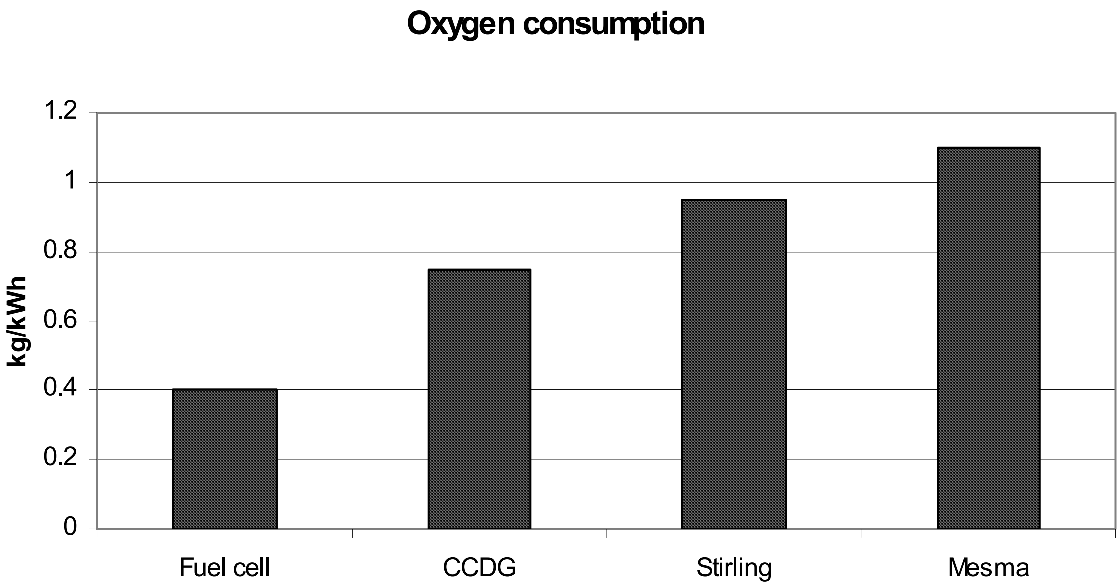

Figure 1: Oxygen Consumption for Four AIP Power Generation Technologies.

Fuel cells convert a fuel and an oxidant directly into electricity by an electrochemical process, which is, in theory, up to 100% efficient. However, practical limitations lower the fuel cell's efficiency, typically to between 40% and 65%. The basic fuel cell stack has no moving parts, can generate electricity silently, is potentially low maintenance with a long operational life, depending on design. The principles of fuel cell operation and construction have been discussed previously [1].

There are several types of fuel cell, operating in different temperature regimes, and typically named according to the type of electrolyte used. Solid oxide fuel cells operate at high temperatures (c. 750-1000 ºC) using ceramic materials as electrolyte and electrodes. They hold promise for use in utility power and naval applications owing to the possibility of using a hydrocarbon fuel directly by either internal reformation to hydrogen and carbon dioxide, or by direct oxidation. Molten carbonate fuel cells operate at around 650 ºC and internal reformation is also possible with these systems. These systems are expected to be useful for stationary distributed power supplies but are also being assessed for the US Navy for use as ship service generators. A 625 kW, shore based, test demonstrator using diesel fuel is to be commissioned in 2003. Phosphoric acid fuel cells operate at 200 ºC and have been extensively developed for stationary applications, but are high cost, have a low power density, and will probably not reach the market place. Alkaline fuel cells have been developed for use in space and automotive applications but currently lag behind in development. In future, the alkaline electrolyte could well find application in the submarine environment, perhaps in conjunction with a direct liquid fuel (see later).

Proton Exchange Membrane Fuel Cell (PEMFC)

This technology has the greatest potential for submarine applications since it offers the highest gravimetric and volumetric power density of all the fuel cell technologies (better than 700 W/kg and 1100 W/dm^3) and operates at up to 80 ºC, with instant start-up. Figure 2 shows the significant improvements in performance achieved by one fuel cell developer, Ballard, through intensive development over the last 13 years.

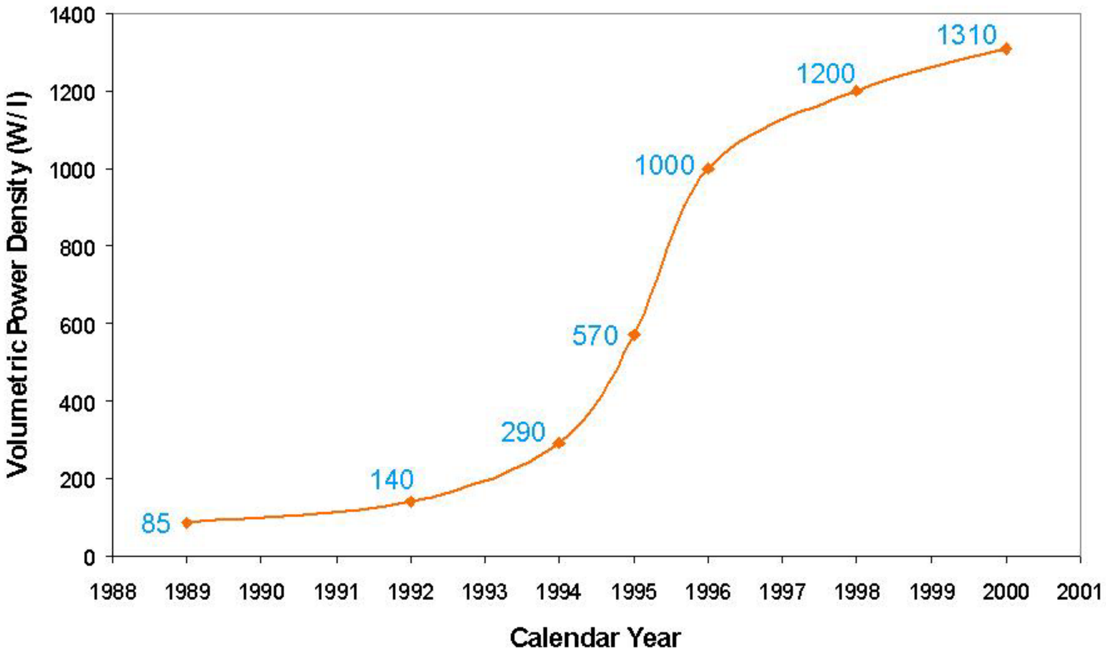

Figure 2: Progress in the Volumetric Power Density of the Ballard Proton Exchange Membrane Fuel Cell (PEMFC) Stack.

The PEMFC is traditionally constructed as a bipolar stack in a filter press arrangement [1]. The working heart of the fuel cell stack is the membrane-electrode assembly. This comprises a thin (20-200 μm) proton-conducting polymer membrane, the electrolyte, to each side of which is applied a layer of carbon-supported platinum catalyst, the anode and cathode. The assembly makes up a negligible fraction of the overall weight of the fuel cell, which includes bipolar plates (for collecting current and distributing the reactant gases), sealing gaskets, and end-plates and tie-rods to supply the required compression. Compression is needed to seal the cells and reduce the interfacial resistance.

Siemens AG were contracted by the German Ministry of Defence in 1970 to develop a FC power-plant for a Class 208 submarine. This project was terminated in 1979 because of the immaturity of the technology – the first iteration used an alkaline fuel cell. Following this, shore trials were conducted through to 1988 using a PEMFC and sea trials were carried out on board a Class 205 submarine. In the last ten years, Siemens have developed a 34 kW PEM fuel cell for module for AIP (see figure 3) and a 300 kW assembly of these modules (see figure 4) is being used on the new Class 212 submarine, the first of which was launched early in 2002. The fuel cell alone will power the submarine to 8 kts; for greater speed, the fuel cell is supplemented by a lead-acid battery in a hybrid configuration. To replace the modules being used in the Class 212 submarine, Siemens are also developing a 120 kW PEMFC that will have higher volumetric and gravimetric power densities than the 34 kW modules.

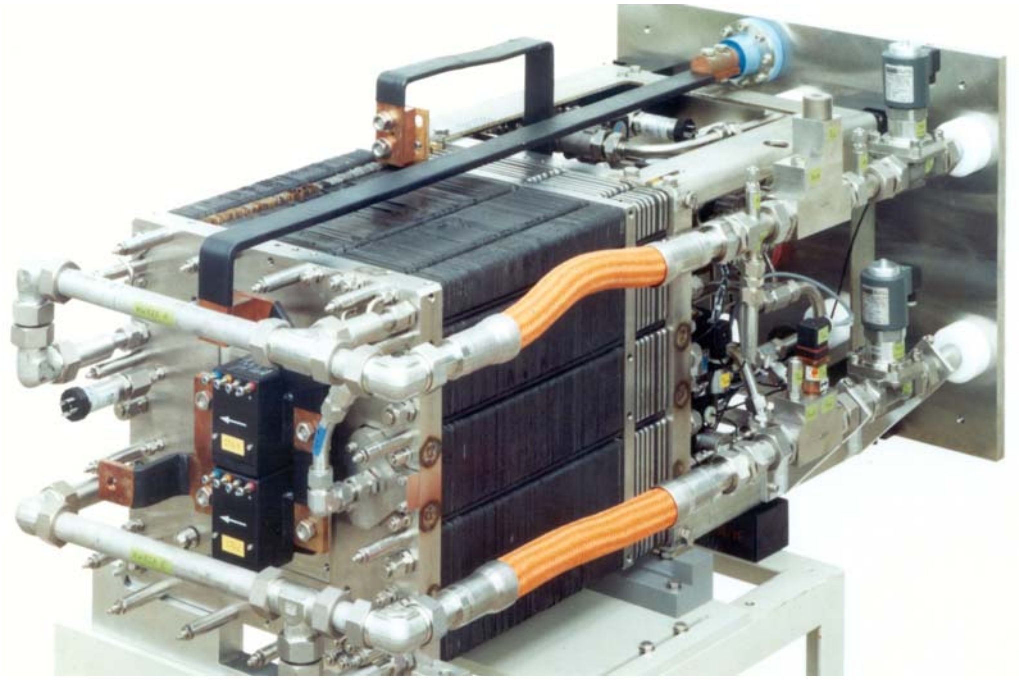

Figure 3: A Siemens PEMFC Module as used on the German 212 AIP Submarine (Source: HDW).

Figure 4: A Siemens 300 kW PEMFC Stack Assembly as used on the German 212 AIP Submarine (*Copyright Jane's Information Group; Source: HDW)*.

One of the major advantages of the fuel cell over the traditional battery is that the power capability of the fuel cell stack can be varied independently of the energy storage capability. When a high energy storage density is required, it is the properties of the fuel and oxidant sub-systems that dominate the overall size of the complete fuel cell plant. The most energy-dense fuel in gravimetric terms is hydrogen, which has a theoretical energy storage density of 33 kWh/kg, compared with diesel and methanol at around 13.2 and 6.2 kWh/kg respectively. One of the greatest challenges is to package hydrogen effectively, particularly for minimum volume for submarine vehicles.

Hydrogen Storage and Generation Technologies

A fuel cell needs a fuel and an oxidant. The fuel of choice is hydrogen and the oxidant is usually oxygen. There are many methods by which hydrogen may be stored or generated but not all will be relevant to submarine applications, for which volume is usually a more important consideration than weight. Compressed gas storage technology has advanced considerably over the last decade because of the US DOE emphasis on hydrogen storage for automotive applications. Advanced, 700 bar, composite cylinders have been demonstrated with a storage capacity of 11 wt% hydrogen, which is roughly equivalent to 2.5 kWh/kg. This figure was recently raised to 13 wt%. The size of cylinders available is limited to automotive applications but would be eminently suitable for unmanned underwater vehicles and swimmer delivery vehicles. The same technology could also be used for oxygen storage.

The beauty of compressed gas storage is the simplicity of the hydrogen storage sub-system. Using the pure reactants – hydrogen and oxygen – also means that the only product is pure water. The disadvantage of compressed gas is the requirement for high performance, power hungry compressors. The volume taken up by the sub-system is also relatively high (figure 5). Storing hydrogen as a cryogenic liquid is assumed to be impractical for underwater applications owing to the extremely low temperatures required. Hydrogen has a very low boiling point at 1 bar of 20 K (-253 ^{o}C) and therefore special insulated containers are required, with attention being paid to the hydrogen lost due to boil off.

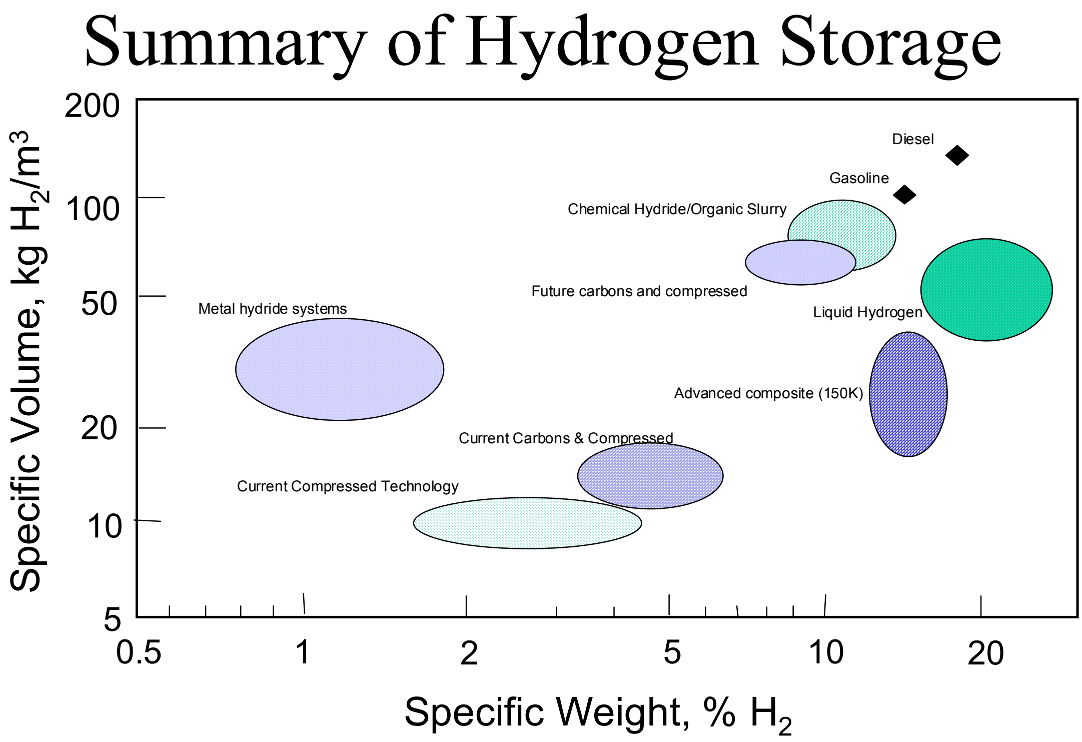

Figure 5: Hydrogen Storage and Generation Technologies.

Two further methods of hydrogen storage will be considered – reversible intermetallic metal hydrides and carbon nanofibres. In addition, hydrogen generation by reforming liquid fuels will also be discussed.

Reversible Metal Hydrides

Certain intermetallic alloys can store and release hydrogen reversibly [2]. These are referred to as reversible or secondary metal hydrides, to distinguish them from the primary metal hydrides, such as lithium hydride, that can only release hydrogen by decomposition, either at very high temperatures or by reaction with water. Many alloys are suitable for storing hydrogen; selecting the best depends on the precise conditions required.

Reversible metal hydrides are a heavy option but on a volume basis are very competitive, better than liquid hydrogen itself (figure 5). Current ambient temperature alloys are capable of reversibly storing up to 1.8 wt % hydrogen and 0.1 tonne H_2/m^3 but, unfortunately, the hydride cannot be densely packed since hydrogen must be able to permeate through the medium. Additionally, the hydriding process is exothermic such that a heat exchanger is required to cool the alloy on charge and to heat it on discharge.

Metal hydrides are the safest method for storing hydrogen because the storage containers are filled with metal hydride and contain virtually no free gas. The pressure in the containers is low (10 to 15 bar) and, because the desorption of hydrogen is endothermic, a rupture of the storage container will only result in a controlled loss of hydrogen. As this leak continues, the alloy will get progressively cooler, which will reduce the leakage rate.

Howaldtswerke Deutsche Werft (HDW) have developed an air-independent-propulsion (AIP) system for the Class 212 submarine [3,4] in which the hydrogen is stored as a metal hydride. This submarine will have 18 hydride tanks, each weighing 4.4 tonnes, with a volume of 1200 litres, and capable of providing 1 MWh of energy per container. The metal hydride is heated by the fuel cell cooling water system to provide the energy for endothermic dehydrogenation.

The positioning of the hydride storage tanks around the outer hull means that their considerable mass can further contribute to reducing low-frequency radiated noise. The hydride storage system is completely maintenance free and can therefore be located outside the main pressure hull.

Carbon Nanofibres

Carbon nanofibre technology is still in its infancy but the hydrogen storage capability is claimed to be very high. The inventors, Baker and Rodriguez, have claimed [5] to have made a new form of carbon that can store up to three times its own weight in hydrogen, under pressure, at room temperature, but the claim has been met with some scepticism. Recent work by the inventors [6] has revised the claims downward but they still report a very respectable 46-68 wt % hydrogen absorption and a release of between 43-58 wt % without heating. The estimated density of the charged fibres is 0.5 g cm^{-3}, giving a volumetric storage density of 0.29 tonne H_2/m^3. The predicted specific energy and energy density for a system using fibres storing 50% hydrogen are 5.7 MWh/T and 4.2 MWh/l respectively, when the weight and volume of the container is included in the calculations.

It should be noted that graphite nanofibre storage is at a very early stage of development and little is known. In fact, there is still some debate over whether it works at all. It has only been tested on a gramme-scale and, even assuming the inventors' claims are correct, many problems may arise on scaling up, especially to the tonne-scale required for submarine propulsion. This technology is the subject of another paper and the reader is referred to this as a source of current information.

Methanol Reformation

The nearest competitor to carbon nanofibre storage system in terms of energy density is methanol reformation. For most land-based applications, a fuel cell will use oxygen from the air as the oxidant as this saves the weight and volume of having to carry an oxygen source. However, for a submarine application, oxygen must be carried. A disadvantage of a fuel cell system that uses a reformate gas as opposed to pure hydrogen is that the reforming system will have a higher oxygen demand. This is because, in addition to operating the fuel cell, oxygen is also required to reform the liquid fuel into hydrogen, either for partial oxidation reforming or to burn a small proportion of the fuel or off-gas to provide the heat for steam reformation. This extra oxygen requirement must be factored into any calculations. A further complication of reforming systems is that carbon dioxide is also produced as a by-product of the reaction and this needs to be stored or disposed of safely and discretely.

Liquid fuels, such as methanol and diesel, have the advantages that they are readily available, may be stored in tanks and have a high energy density. Often, these advantages outweigh the complications introduced by a reformer.

Carbon monoxide is a potential by-product of the reformation process. This is a reversible poison for the platinum catalyst used in PEM fuel cells and therefore purification of the gas is required before it is fed to the fuel cell.

A steam reforming system suitable for a submarine needs might comprise:

- a storage vessel for methanol,
- a storage vessel for oxygen,
- a steam reformer assembly,
- a gas purification stage,
- a CO_2 handling system.

The CO_2 produced during reforming must be stored on board the submarine or discharged into the sea with a minimum signature and energy loss. Carbon dioxide has a high solubility in water and, if necessary, could be discharged without producing bubbles by pre-dissolving the gas.

Methanol is a liquid at room temperature and could be stored in tanks. The methanol will be consumed as it is used by the fuel cell, and a hard conformal tank would require compensation to accommodate the changing volume to prevent it collapsing. Direct water contact with methanol is unacceptable because the two are miscible. External storage of methanol in soft conformal bags is a possibility. The bags would be fabricated from methanol-resistant material and, during operation, the seawater would naturally displace the consumed methanol without coming into contact with it.

Methanol is a toxic, flammable liquid that burns without a flame but is easily contained and therefore, if the system is correctly designed, it should not pose a safety hazard. A methanol reformer for submarine applications is being developed under HDW sponsorship. There is also considerable interest in methanol reformer systems for use in cars and buses.

Diesel Reformation

The most abundant fuels used in the world are derived from crude oil. Crude oils are complex mixtures consisting primarily of hydrocarbons and other compounds containing sulphur, nitrogen, oxygen and trace metals. The principal fuels are made by fractional distillation of the crude petroleum. Diesel fuel has very high volumetric and gravimetric energy densities (see Table 2).

Table 2: Properties of Methanol, Kerosene and Diesel

	Methanol	Kerosene	Diesel
Formula	CH_3OH	$C_{9.3}H_{18.1}$	$C_{13.9}H_{22.6}$
Flash point (^oC)	11	43	52
Wt percent H_2 produced	18.8	32.5	31.4
Vol density of H_2 (kg H2/L)	0.071	0.266	0.267
Calorific energy density (kWh/L)	3.95	10.48	10.51
Calorific specific energy (kWh/kg)	4.97	12.8	12.37
Fuel volume for 1 MWh (m^3)	0.50	0.22	0.23
Fuel weight for 1 MWh (T)	0.40	0.18	0.19

Both diesel and kerosene have more than double the energy density of methanol. Unfortunately, the reformation of diesel is more technically difficult than reformation of methanol, and the overall chemical to electrical conversion efficiency of the fuel is only likely to be about 30%, compared with methanol at 55-60%. Diesel also contains appreciable quantities of sulphur compounds, which are poisonous to the conventional reformer and fuel cell catalysts.

The much higher temperatures required for diesel reformation add to the complexity of a reformer system and reduce the conversion efficiency compared with methanol. The gas clean-up process is more complicated than for methanol since hydrogen sulphide, as well as carbon monoxide, must be removed. The main advantages of diesel fuel include:

- excellent volumetric and gravimetric energy densities,
- current military logistic fuel,
- extensive distribution network.

Its main disadvantages are:

- requires desulphurization,
- requires high pressure and temperature,
- reformer exhaust gas by-product must be managed (stored or discharged),
- higher oxygen demand than H_2 storage systems.

Cleaner hydrocarbon fuels such as kerosene or gasoline could be reformed. Kerosene is a common commercial and strategic distillate used in a broad range of applications from lanterns to jet fuel. It is less volatile than gasoline and has a higher flash point to provide greater safety in handling. It has a much lower sulphur content than diesel fuel and can be reformed more easily.

Direct Oxidation of Liquid Fuels

Alcohols and hydrocarbons can, in theory, act as fuel for a fuel cell and be directly oxidized like hydrogen. One of the commonest fuels of this type is methanol, which is used in the direct methanol fuel cell (DMFC).

The direct oxidation of large hydrocarbons such as decane, petroleum and sulphur-free diesel has been demonstrated in high temperature (750-1,000 °C) solid oxide fuel cells, which would yield a high energy, liquid fuel. However, the high operating temperature, and the need to dispose of carbon dioxide and other detectable by-products, make these systems unsuitable for covert operations.

Oxygen Storage

All AIP power generation options require the storage and consumption of oxygen. Primary systems store the O_2 in either its gaseous or liquid form. Gaseous storage requires the use of large heavy tanks and, while the use of composite materials would reduce the weight penalty, the cost could be excessive for large platforms but acceptable for smaller ones. Composite cylinders would still suffer from a relatively low volumetric performance. LOX systems include the cryogenic storage of O_2 in subcritical and supercritical form. Subcritical O_2, which appears to be the most commonly used technique, is maintained in the liquid state at extremely low temperatures (< -118.6 ^oC) and at high pressures (3- 55 bar). It is also possible to store O_2 as a supercritical fluid (> -118 ^oC, >50 bar), which removes the tendency to slosh. This could be advantageous in a submarine where trim may be affected by the changing distribution of liquid, although internal baffles could be used. Secondary systems provide O_2 through chemical reaction. The alternatives are chlorate candles, superoxide and hydrogen peroxide. Primary storage in liquid form is the optimum choice, as shown in figure 6.

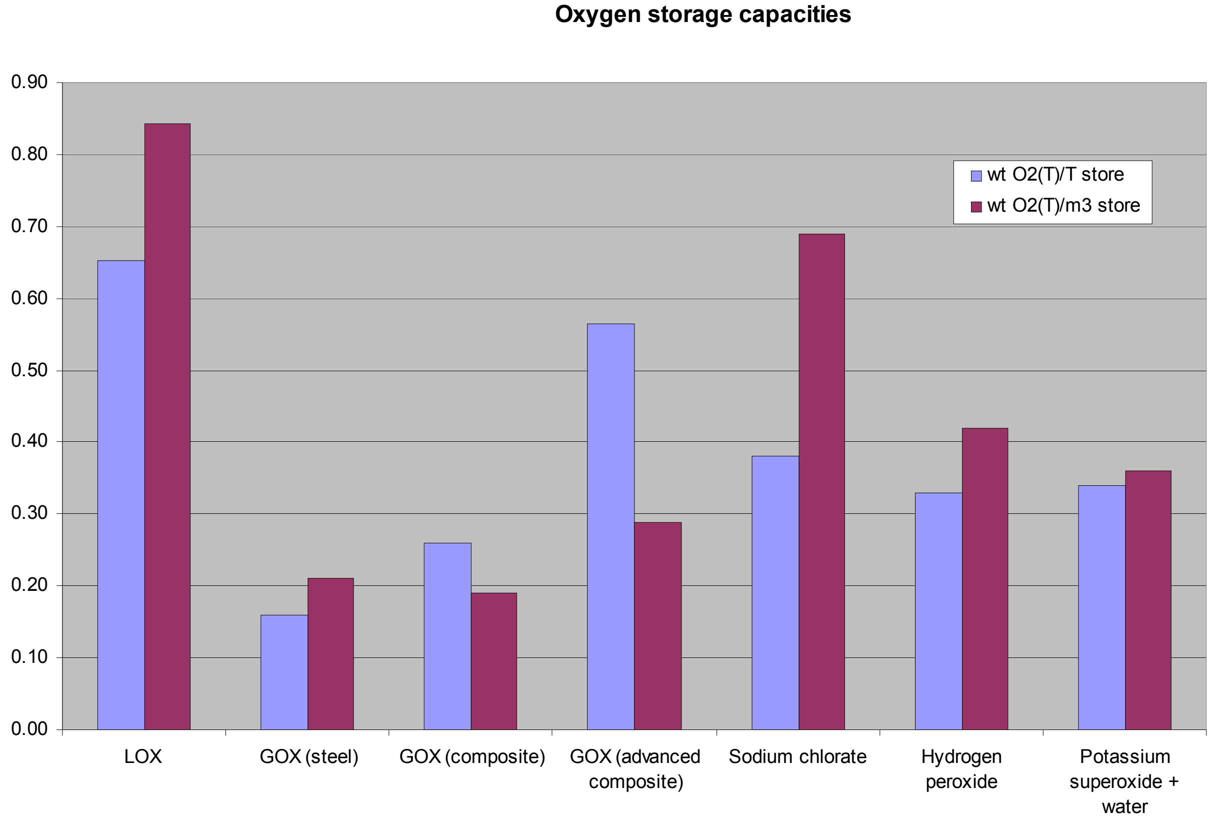

Figure 6: Oxygen Storage and Generation Technologies.

There seems to be a growing acceptance that the use of LOX is necessary for a successful AIP system on manned platforms, and several countries are now considering using it. The Swedish Navy have been assessing its use since 1967. In 1988, a Stirling-based section, which included a small cryogenic tank, was inserted into the submarine Näcken. This research culminated in the launch of the world's first series-constructed, non-nuclear submarine with an AIP system incorporating LOX at Kockums, in Malmö, in 1995. In the Class 212 submarines, LOX is stored in super-insulated tanks that are mounted inside the outer casing but outside the pressure hull. The pressure vessel (figure 7) is specially designed to withstand shock load and diving pressure, and is manufactured from the same material as the submarine hull. Each tank (two in the 212 class) has its own evaporator, which ensures that no LOX enters the submarine.

Figure 7: A LOX Tank on the German 212 AIP Submarine (Source: HDW).

Locating LOX tanks outside the pressure hull provides a greater degree of safety, although internal storage is practised, and models have demonstrated acceptable risk. In fact, internal LOX storage has been suggested for the new U-214 design. In Italy, Fincantieri produce the S-500 submarine using AIP with internally mounted LOX tanks to provide oxygen to a closed cycle diesel engine. The storage of LOX raises many safety issues, such as the effects of leakage, boil-off or large shock loads. Moving parts and the presence of lubricants could create conditions for dangerous accidental reactions. The LOX tanks and pipes need to be highly reliable to accommodate the low temperature (-180 ^{o}C) required for LOX storage and, whilst some of the hazards have been identified, a full safety/risk assessment will be required before LOX is stored on UK submarines. On manned vessels, the boil-off from the LOX tanks can be used to supply crew's oxygen, thereby replacing the present electrolysers used on nuclear vessels, or the compressed air storage and oxygen candles used on conventional vessels. Certainly AIP will significantly increase submerged endurance and reduce detectability. The longer underwater duration will ensure that conventional AIP vessels require new methods for supplying crew's oxygen; harnessing the boil-off of the oxidant supply for the AIP system would be a convenient and efficient method of achieving this. Each crew member requires about 1 kg of O_2 per day for life support. Thus the mass of oxygen required for a 50-day patrol with a crew of 50 is about 2.5 tonnes.

It is likely that LOX will remain the oxidant of choice for manned platforms, where oxygen is required for the crew. For unmanned systems, hydrogen peroxide is being evaluated as a serious alternative.

Metal-Oxidant Semi Fuel Cells

Aluminium-oxygen systems are currently in use in the Canadian and US militaries for AUV/UUV power. A system has been developed by Alupower in the USA, which uses oxygen stored as a compressed gas, and has an energy density of 265 Wh/kg and per litre. The Canadian ARCS vehicle uses a system where the oxygen is generated from hydrogen peroxide, but has a similar energy density. The developers of the ARCS power source, FCT, have a target energy density of 400 Wh/kg for an aluminium-oxygen system using hydrogen peroxide as the oxidant.

The Naval Underwater Warfare Center (NUWC), Newport RI, USA, are developing a similar system to the ARCS UUV with a target specific energy of 400 Wh/kg. Beyond this, NUWC are undertaking development of a magnesium-hydrogen peroxide system, with a target specific energy of 550 Wh/kg. These systems are only currently being considered for AUVs/UUVs.

Technical Issues and Integration

Oxygen storage is a mature technology being accepted by several navies as the favoured option for storing the oxygen for AIP systems. In contrast, hydrogen storage technologies are at an early stage of development with new systems being proposed, so the system of choice is not yet identified. The major advantages and disadvantages of the four main hydrogen storage or generation system are summarised in table 3.

Table 3: Comparison of Hydrogen Storage and Generation Technologies

Technology	Advantage	Disadvantage
Metal hydride	Good volumetric density Pure hydrogen liberated Ambient temperature operation Proven technology of suitable scale	Poor gravimetric density
Carbon nanofibres	Excellent gravimetric and volumetric energy densities claimed Pure hydrogen liberated Ambient temperature operation	Technology not proven Cycling ability unknown
Methanol reformation	Good gravimetric and volumetric energy densities No sulphur produced Liquid fuel	Requires reforming High oxygen demand CO_2 disposal
Diesel reformation	Very good gravimetric and volumetric energy densities Logistic fuel Inexpensive	Requires reforming Sulphur impurities Higher oxygen demand High temperatures required CO_2 and other emissions Technically difficult/not proven

THE MANNED AIR-INDEPENDENT PROPULSION SUBMARINE CASE

The covert AIP submarine for littoral operations will probably use a hybrid power system comprising an energy store for uninterruptible power and peak lopping, and a power generator, ideally a fuel cell, for stealthy base-load power and charging the energy store. If very long transits are required, a third component of the hybrid power system could be a fully integrated nuclear reactor.

In figure 8, the energy stored in an 82 m^3 volume is graphically presented for a PEMFC with various fuel options. The graph shows the volumes and containment for different fuels, with an equivalent amount of

LOX. It also shows the effects of operating the PEMFC at different cell voltages, which in turn affects fuel cell efficiency. There is a trade-off between the power density and size of the fuel cell stack and the specific fuel consumption.

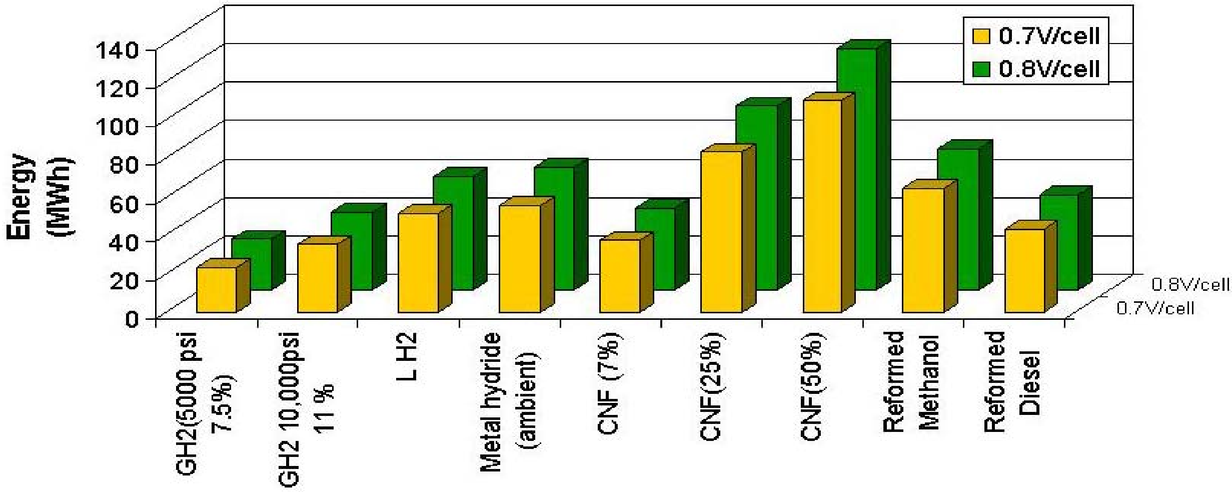

Figure 8: The energy available in an 82 m^3 space for a PEMFC with different hydrogen storage and generation options, with an equivalent amount of LOX. Values include reactant containment but not packing factor. The influence of fuel cell efficiency on hydrogen consumption is also indicated by data for two cell operating voltages.

To obtain a more complete comparison between various PEMFC + fuel options, the lead-acid battery and the CCDG, the weights and volumes of the entire system need to be considered, including the hydrogen, oxygen, fuel cell, and reformer if required. Table 4 is an example for a 12.6 MWh, 600 kW system. The values quoted include storage tanks but not packing factors.

Table 4: Alternative Energy Components for a 12.6 MWh, 600 kW Air-Independent Propulsion System

Type	LOX[1]		Fuel		Generator		**Totals**	
	Vol/m3	Wt/T	Vol/m3	Wt/T	Vol/m3	Wt/T	**Vol/m3**	**Weight/T**
Fuel cell & carbon nanofibres (7%)	6.4	8.2	21.4	15.3	0.9	0.5	**28.7**	**24.0**
Fuel cell & carbon nanofibres (25%)	6.4	8.2	6.0	4.2	0.9	0.5	**13.3**	**12.9**
Fuel cell & carbon nanofibres (50%)	6.4	8.2	3.0	2.2	0.9	0.5	**10.3**	**10.9**
Fuel cell & reversible metal hydride	6.4	8.2	12.2	52.4	0.9	0.5	**19.5**	**61.1**
Closed cycle diesel generator	11.3	14.5	5.4	4.4	18.8	15.0	**35.5**	**33.9**
Methanol reformer & fuel cell	9.3	12.2	6.8	5.9	7.1	13.8	**23.2**	**31.9**
Lead acid	0.0	0.0	132.6	393.8	0.0	0.0	**132.6**	**393.8**

[1] LOX values exclude crew air

The hydrogen and oxygen storage systems scale with the energy requirement, and the size of the generator system scales with the power demand. Therefore, if technologies have a large generator component (e.g., PEMFC + reformer, or diesel generator), it will form a significant fraction of the total system for high power, low energy demands. If the power requirement were to be kept constant but the energy requirement increased, the closed cycle diesel generator and methanol reformer with fuel cell systems would become more competitive.

The lightest and, more importantly, lowest volume system is a fuel cell with carbon nanofibres storing 50 wt % hydrogen. Even if carbon nanofibres only manage 25% performance, they still offer the best system. If nanofibre technology proves not to be feasible, the two next best alternatives, in terms of volume, are either metal hydride storage or methanol reformation. The metal hydride system as used on the Class 212 is much simpler than a methanol reformer but is much heavier. In fact, the metal hydride system is so heavy that extra flotation volume is required to maintain neutral buoyancy, and this will limit the range that can be achieved, so methanol reformation is preferred over a metal hydride system.

The least complex systems will also be the hydrogen storage systems, such as metal hydrides and carbon nanofibres, which will provide pure hydrogen to the fuel cell. The only by-product from the fuel cell will be pure water.

The reforming systems are more complex. The fuel and steam must be fed into the reformer and heated by burning the off-gas in oxygen. The reaction will produce hydrogen for the fuel cell and carbon dioxide and other by-products, which must be stored or disposed of discretely. Other impurities that may be produced during reformation, such as carbon monoxide and hydrogen sulphide, will have to be removed before the gas can enter the fuel cell. Once discharged overboard, they will make the submarine more vulnerable to detection than if a pure hydrogen/oxygen system were used. Hence, for covert operations in littoral waters, either a pure hydrogen fuel must be used, or the by-products from fuel combustion or reforming must be stored until it is safe for them to be discharged.

There are many possible physical configurations for an AIP system. Fuel cells are modular units, which could be sited in different zones of the vessel. This would aid the survivability of the submarine. For hydrogen storage technologies, the use of containers distributed throughout the boat would improve survivability with little weight or volume penalty. It would be less efficient to use a number of reformer modules, although the survivability of the boat would be improved by adding some redundancy to the reforming system.

The AIP system developed by HDW [3,4] for the Class 212 has been mentioned earlier. Over a long mission, it is possible to provide the hydride storage system with more heat than is needed to release the hydrogen. Because of the increase in storage temperature, pressure in the cylinder rises slightly. This absorption of heat by the alloy enables the submarine to operate in a thermally enclosed state. The hydride storage system is completely maintenance free and can therefore be located in the outer hull area of the submarine without any difficulty. Positioning the hydride storage tanks around the outer hull also means that their considerable mass can further contribute to reducing low-frequency radiated noise. The oxygen will be stored as a liquid in two tanks placed outside the pressure hull (figure 7). Each tank has its own evaporator, which ensures that no LOX enters the submarine.

Although it is safer to store the LOX outside the pressure hull, with the correct safety control, internal LOX storage can be configured with an acceptably low risk. Internal LOX storage has been suggested by HDW for the new U-214 design and for their retro-fittable plugs. The AIP insert being offered to other navies by HDW stores the LOX inside the pressure hull and, to save space, the metal hydride containers are outside the pressure hull.

The existing diesel generator compartment on either a SSN or SSK could also be used to accommodate a fuel cell system, and a fuel processor, if required. Figure 9 shows the results of modelling the insertion of various PEMFC/fuel options, and the CCDG, into the space taken up by the auxiliary DGs and their fuel store on a current SSN. In each case, LOX is the oxidant store. The plot of speed against submerged range again illustrates the potential benefits of carbon nanofibres storing hydrogen at 50 wt%, or even 25 wt%. Further benefits would follow the storage of LOX and hydrogen (or fuel to be reformed) outside the pressure hull. The fuel cell could be designed to operate on air or oxygen, which would reduce the amount of LOX required, as air could be used when the boat is on the surface or snorting. This system would have a major advantage over the current diesel electric generator in that it could be operated with the submarine submerged by using LOX, therefore greatly improving the underwater endurance and stealth of the submarine. The system would also benefit a conventional SSK, where it would reduce the boat's indiscretion ratio by allowing it to transit submerged for a greater distance before it would need to surface or snort. For a SSN, it would provide a longer submerged endurance on reactor failure.

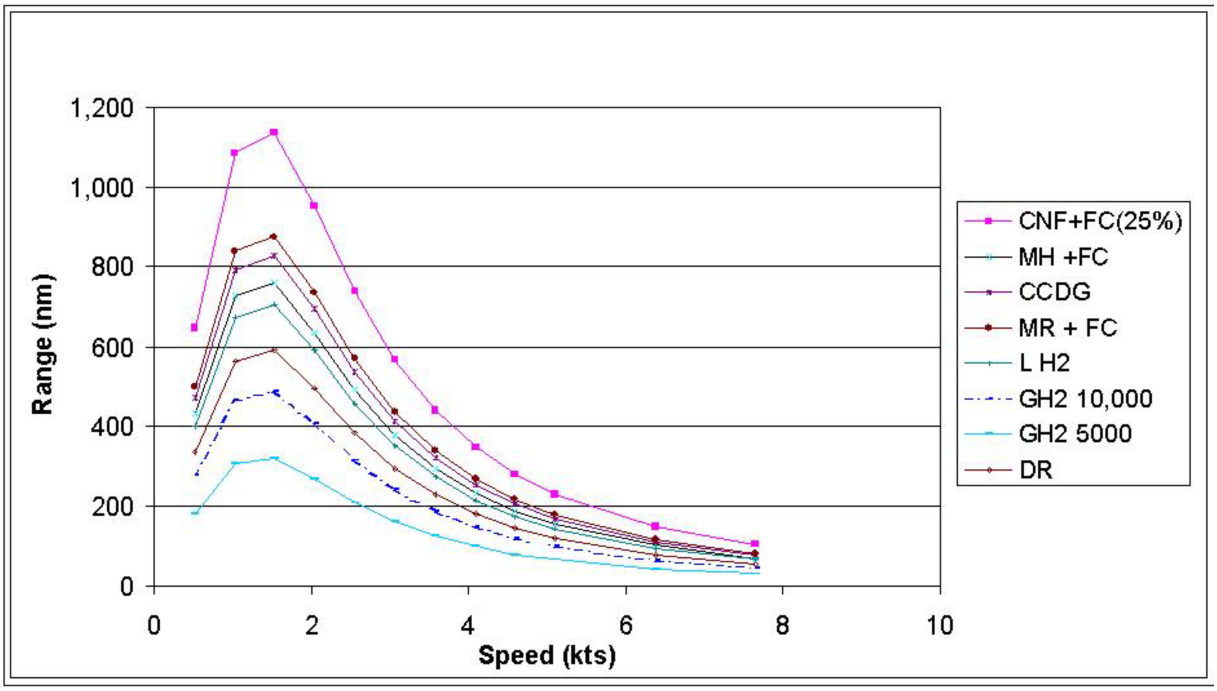

Figure 9: Modelling results for underwater ranges at different speeds for a modern nuclear submarine where the auxiliary diesel generators and fuel store are replaced by an AIP system. Plots are shown for a 600 kW proton exchange membrane fuel cell with different fuel options, compared with a 600 kW closed-cycle diesel generator.

UNMANNED UNDERWATER PLATFORMS

Similar AIP solutions are applicable to smaller platforms because most power sources, particularly fuel cells and batteries, are eminently scaleable. An example is Marlin, a 21-inch, tube launched, mine reconnaissance vehicle (figure 10), which typically cruises at 5 knots.

Figure 10: The 21-inch, Tube Launched, Mine Reconnaissance Vessel Marlin.

An analysis was made of installing different fuel options with a PEMFC in the battery compartment and LOX in the oxidant store, and comparing them with using an advanced, rechargeable, lithium-ion battery (see table 5). Containment of fuel and oxidant was taken into account.

Table 5: A Comparison between PEMFC Power Source Options for Marlin and the Lithium-Ion Battery

H2 store/fuel	Energy Wh	Power source weight kg	Specific energy Wh/kg	Energy density Wh/L
Compressed gaseous hydrogen (5000 psi 7.5%)	70117	127	554	270
Compressed gaseous hydrogen (10,000psi 11%)	106505	152	699	410
Liquid hydrogen	154662	174	891	595
Metal hydride (ambient)	145606	752	194	560
Carbob nanofibres (7%)	111414	240	465	429
Carbon nanofibres (25%)	249236	279	893	959
Carbon nanofibres (50%)	328264	302	1086	1263
Lithium-ion rechargeable	78000	557	140	300

As for the larger manned submarine, hydrogen stored in carbon nanofibres at 50 or even 25 wt% provides the greatest submerged operational endurance. In fact, all fuel options, except hydrogen stored at 5,000 psi, offer better performance than the lithium-ion battery. Similarly the aluminium-hydrogen peroxide system, with its target energy density of 400 Wh/kg, offers a significant performance advantage over the lithium-ion system, and even over the more exotic zinc-silver oxide battery. If magnesium, or even lithium anodes, are successfully developed the metal anode semi-fuel cell will rival the PEMFC for small submersible applications, and hydrogen peroxide will be an alternative oxidant.

CONCLUSIONS

For covert littoral operations, submerged platforms have a key role, and stealthy propulsive and surveillance power is required. This is best provided by an integrated, hybrid, air-independent propulsion system in a full electric architecture.

Of the current AIP power generator options, the proton exchange membrane fuel cell (PEMFC) is the most stealthy, fuel efficient, option for all sizes of platform. The ideal fuel option would be hydrogen stored in a reversible metal hydride, or in compressed form using an advanced, high performance, composite cylinder. If it really works, carbon nanofibre hydrogen storage could revolutionize fuel cell exploitation. The ideal oxidant, particularly for large platforms, is oxygen, stored as a liquid. For smaller platforms, hydrogen peroxide looks a more attractive oxidant, and a metal anode, such as aluminium, magnesium or lithium, might be a more attractive fuel than hydrogen.

REFERENCES

[1] Mepsted G, Green K, Lakeman B, Slee R, Jones P, Moore J and Adcock P. *Man-Portable Fuel Cell System. Part I: Fuel Cell Stacks and Integration,.* J Defence Science, **4** 441 (1999).

[2] Browning D, Mepsted G and Lakeman B. Man-Portable Fuel Cell Systems Part II: Hydrogen Storage and Generation Methods, J Defence Science, **4** 450 (1999).

[3] Sattler G. Journal of Power Sources, **71** 144 (1998).

[4] Sattler G and Pommer H. *Storage of Reactants for PEM FC Systems Aboard Submarines.* WARSHIP '96, International Symposium on Naval Submarines (5 June 1996).

[5] Hills S. New Scientist, December 20 (1996).

[6] Chambers A, Park C, Baker R T K and Rodriguez N M. *J. Phys Chem B,* **102(22)** 4253 (1998).